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Some Lessons from Air Pollution

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The Agricultural Economics of Environmental Change: Some Lessons from Air Pollution

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The agricultural consequences of global climate change are the latest in a series of major environmental concerns facing policy makers. As agencies begin to consider investments in global climate change research, it is instructive to examine existing conceptual and empirical analyses of similar problems. In this paper, we explore the understanding that economists have acquired about the consequences of air pollution-induced crop damages. These studies address research questions likely to arise in global climate change research and thus reduce the initial information required to understand the agricultural implications of climate change. A set of nine common themes is drawn from the extant literature. In addition, unique research challenges likely to emerge in climate change assessments are discussed.

Keywords: economics, air pollution, global climatic change, environmental policy.

1. Introduction

Global climate change arising from increases in atmospheric CO_2 and trace gas concentrations is the latest in a series of major environmental concerns facing regulatory agencies. Numerous studies document the general causes and implications of the changes likely to occur over the next 50 to 100 years, (e.g. Katz, 1977; Lough, Wigley and Palutikof, 1984; McQuigg, 1982; National Research Council, 1985). While there is controversy about the exact magnitude of climate change during this period, the consensus appears to be that the Earth's climate will warm substantially (1·0° to 4·5°C) (Hansen, 1986; Hansen, *et al.*, 1984; Mearns, Katz and Schneider, 1986).

Global climate changes can affect virtually all ecosystems and ecosystems service flows (Wigley, Ingram and Farmer, 1981; Lough, Wigley and Palutikof, 1983). One ecosystem of particular importance to human welfare is monoculture agriculture. The

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human consequences of crop failure arising from climatic change are apparent. Recent notable examples include the famine in Africa caused by prolonged drought (Glantz, 1985) and the 1988 drought in the United States Corn Belt. While the levels of human suffering undeniably differ in these two examples, they provide dramatic evidence of the susceptibility of agriculture and its constituencies to even short term changes in regional climatic patterns.

Several studies describe the kinds of climate change that can affect agricultural yields (e.g. Decker, Jones and Achutuni, 1979; Rosenzweig, 1984; and Callaway *et al.*, 1985). Included are elevated atmospheric CO_2 concentrations and temperatures. These can lead to increased pest and pathogen populations and reduced irrigation water supplies. Increased tropospheric ozone and surface incidences of UV-B radiation have also been indicated. However, forecasting the exact magnitude and geographical distribution of these yield changes is a challenging task. Once measured, such yield responses must then be translated into economic or other measures of human welfare for use in policy formation. If past environmental issues are any indicator, each of these tasks will require considerable research resources before policy makers choose to try to influence climate change precursors.

As agencies and political bodies begin to consider major investments in research on global climate change, it is instructive to examine existing conceptual and empirical analyses of similar problems. In this paper, we explore the understanding that economists and plant scientists have acquired to date about the economic consequences of air pollution-induced vegetation damages on agriculture. Much of this publicly funded research is prototypical of the interdisciplinary approach needed in researching global climate change. These studies also address research questions likely to arise in such an effort. These predecessor analyses can thus guide and reduce the initial information required to understand the economic implications of climatic change for agriculture. They also provide insight into global climate research efforts likely to offer the greatest improvements in current knowledge.

2. The economic assessment problem

2.1. THE BIOLOGICAL PROBLEM

Assessments of the economic consequences of environmental change require information on how the change relates to things that people value, such as food and fiber. Plant scientists generate biological response information, typically by performing controlled experiments on plants of a given cultivar and species. This basic science, piece-by-piece approach to the study of how environmental change affects vegetation makes truly awesome the task of covering and synthesizing the feasible or even the technically efficient input combinations that determine yields. In agriculture, environmental and edaphic factors create thousands of different types of inputs. Each input type is, in turn, embodied in one or more production processes or crops, which may appear in a variety of cultivars and which can be put to many distinct uses. Moreover, environmental cofactors, such as moisture and temperature, may act in concert with the variable of interest to alter its impact.

One key problem then is to decide how much and what kind of plant science information to generate and retain in any particular problem setting. Specifically, when one of the several objectives of plant science studies is to provide information useful for estimating economic consequences, a basic question is whether more or less natural

science detail will alter the economic estimates in a non-trivial way. Both the plant scientist and the economist must refine their knowledge such that the relations between environmental change and vegetation effects are defined in dimensions which are simultaneously coherent, consistent with consensus biological, chemical, and economic principles, and which correspond to those in which growers choose to define them (Adams and Crocker, 1985).

An example of an integrated approach to agriculture effects research is the U.S. Environmental Protection Agency's National Crop Loss Assessment Network (NCLAN). Begun in 1980, NCLAN is a multi-site, multidisciplinary program under which field experiments have been conducted on the yield responses of major U.S. crops to ozone, the primary oxidant air pollutant. The experiments were designed in collaboration with economists to support economic assessments. They therefore placed more emphasis upon substitution possibilities among inputs and among cultivars than is traditional in such experiments. As these experiments progressed, questions arose regarding the sensitivity of economic benefit assessments to improved biological yield-response data. Several studies with the NCLAN data, including Crocker (1982), Adams, Crocker and Katz (1984), Adams and Crocker (1984), Howitt, Gossard and Adams (1984), Kopp *et al.* (1985), and Adams and McCarl (1985), have now demonstrated that there are some important classes of pollution impacts upon agriculture in which rather imprecise yield-response information is quite adequate for distinguishing among the economic consequences of alternative ambient pollution levels.

In their Bayesian inquiry into the robustness of economic estimates of crop damages from ambient ozone, Adams, Crocker and Katz (1984) showed that the policy value of additional plant science yield response information declines rapidly. Forty or fewer yield response observations per crop, similar to those found in Heck *et al.* (1982) adequately discriminated among the differences in economic surplus in U. S. production of corn, cotton, soybeans, and wheat that ambient ozone levels of 66, 53, and 40 parts per billion generated. In an entirely different setting, Feinerman and Yaron (1983) demonstrated that the net value of information to Israeli growers about potato yield responses to soil salinity was maximized with as few as 15 and not more than 27 observations.

Adams and McCarl (1985), while studying the economic benefits of ambient ozone control for corn, soybeans, and wheat grown in the U.S. Corn Belt, found that changes in key natural science parameters had to be substantial if they were to translate into major changes in benefit estimates. For given pollution levels, yield responses across alternative cultivar selections and across temporal and spatial variations tended to be homogeneous, implying that additional yield-response observations do not greatly affect economic benefit estimates. Even where some disparate cultivar, spatial, and temporal responses were observed, their effect on benefit estimates was not as great as was the effect of using the NCLAN data rather than yield-response data not generated with economic assessments in mind. Adams and McCarl (1985, p. 274) concluded "... that even a limited set of crop response data, when generated in accordance with the needs of those doing the assessments, appear adequate to measure the general benefits of pollution control."

Adams and McCarl (1985) add two strong qualifications to this conclusion, however. First, they note that Tingey *et al.* (1982) hypothesize that climatic and soil factors are important in modelling the real-world effect of ozone on crop yields. The NCLAN data confirm the biological importance of the interaction between moisture stress and ozone, generally showing that water stress tends to dampen negative yield effects. When response functions reflecting these moisture stress–ozone interactions were included in

the economic analysis, the changes in benefit estimates were as great as 50%. This result could be due to the fact that plants grown under commercial conditions in the U.S. Corn Belt typically suffer from some form of moisture stress, while the NCLAN experiments were initially designed to be well-watered.

Adams and McCarl (1985) also warn that their results are only the latest in a succession of studies, (e.g. Day, 1965) showing that yield response and economic benefit-estimates are sensitive to the form and the stochastic properties of the yield-response function. The Adams and McCarl (1985) benefit estimates differed by as much as 60% according to whether a linear or a non-linear (Weibull) yield response function was employed. This result is similar to that found between the linear and quadratic forms by Adams, Crocker and Katz (1984). Note, however, that while some plant scientists suggest the Weibull (1951) distribution as useful for studying yield responses to pollution (Rawlings and Cure, 1985), most nonlinear forms seem to give very similar results (Atkinson, Adams and Crocker, 1985).

2.2. THE ECONOMIC PROBLEM

Assessments of the economic consequences of environmental change try to estimate differences in income equivalents, defined as differences in the sums of buyer surpluses and seller quasi-rents over two or more policy relevant pollution levels. Buyer surplus portrays the difference between the maximum a representative individual would be willing to commit himself to pay for a commodity unit and what he in fact has to pay. Similarly, seller quasi-rent is the difference between what a commodity owner receives for supplying a commodity unit and the minimum he must receive in order to be willing to commit to that supply. The sum of seller quasi-rent and buyer surplus is thus a measure of the prospective net benefits from the production and the consumption of a commodity. The observable unit prices of other commodities that could provide equal satisfaction set an upper bound to the buyer's maximum willingness-to-pay; the earnings his resources could obtain in other activities set a lower bound on the minimum reward the seller must receive. Maximum willingness-to-pay represents demand; the minimum necessary reward defines supply.

A complete assessment of economic consequences requires three kinds of information: (1) the differential changes that pollution control causes in production and consumption opportunities; (2) the responses of input and output market prices to these changes; and (3) the input and output changes that affected individuals make to minimize losses or maximize gains from changes in production and consumption opportunities and in the prices of these opportunities. Natural science studies are the primary source of information for the first requirement. Evaluation of the latter two requirements represents the economics portion of benefits assessment. If an environmental change causes substantial changes in outputs, price and quality changes can occur which, in turn, lead to further market-induced output changes. Moreover, even if prices remain constant, natural science information will still fail to provide accurate indications of output changes when individuals can alter production practices and the types of outputs produced. Thus, accurate information on the economic consequences of environmental change for agriculture can be achieved only if the *reciprocal* relations between physical and biological changes and the responses of individuals and institutions are explicitly recognized.

3. Empirical evidence

The above discussion summarizes the biological and economic problems embedded in economic assessments of environmental change. It also suggests the need for an integrated approach in implementing such protocols for policy analysis. This section reviews specific NCLAN or NCLAN data-based assessments that provide empirical evidence of the economic consequences of ozone pollution on U.S. agriculture. Table 1 portrays the conditions specified and the empirical results obtained for these selected studies. With the exception of the duality study of Mjelde *et al.* (1984), the remaining studies cited in the table employed simulation, particularly mathematical programming approaches.

Caution should be exercised in trying to compare numerical estimates across these studies given that crops, response information, and assumed economic and environmental conditions differ considerably. However, even though numerical estimates and the conditions under which they were derived may differ, the NCLAN-based studies exhibit common patterns of behavioral responses and sensitivities to imposed conditions and to data accuracy and precision. These commonalities both serve to summarize the major findings arising from prior NCLAN research and can serve to restrict the dimensions of their analytical and empirical problems. Most of these commonalities follow directly from economic theory; others are more subtle and arise from the characteristics of the agricultural setting. Together, they serve as a summary of current understanding of ozone's economic consequences. They also offer a set of priors on which to base research directions for future assessments of environmental change.

1. *Increasing air pollution causes losses in the total economic surplus from the production and consumption of agricultural outputs to increase at an increasing rate.* The estimates of the following studies display this pattern: Howitt, Gossard and Adams (1984); Adams and Crocker (1984); Adams, Crocker and Katz (1984); Kopp *et al.* (1985); Adams and McCarl (1985); Adams, Crocker and Katz (1985); Adams, Hamilton and McCarl (1986); and Shortle, Dunn and Phillips (1986). No thoroughly consistent pattern emerges as to the absolute magnitudes of this rate of change in total surplus.

2. *Growers can gain from increases in air pollution.* Adams and McCarl (1985) found that substantial increases in ozone increase the quasi-rents of Corn Belt growers. Shortle, Dunn and Phillips (1986) also estimated that Corn Belt growers benefit from ozone increases. A sufficient condition for these findings is that the pollution-induced percentage reduction in output quantity for a given crop be less than the percentage increase in market price that the supply reduction causes. When secondary effects on livestock producers are included in national assessments, the net effect on all producers of ozone increases is a loss in welfare (Adams, Hamilton and McCarl, 1986). Even here, however, producers in some regions benefit while others lose. Pre-NCLAN studies generally conclude that growers always lose from increased air pollution. However, those studies typically disregard market price changes and therefore guarantee producer losses with increased pollution. Such studies cannot be taken seriously as evidence supporting the hypothesis of universal producer losses.

3. *Losses to consumers are a significant portion of the total losses that air pollution causes agriculture.* Of the studies that accounted for air pollution-induced changes in the prices of agricultural outputs, consumer surplus losses as a percentage of total losses range from a low of 50% (Adams, Hamilton and McCarl, 1986) to a high of 100% (Adams and McCarl, 1985). Given that producers can sometimes benefit from air pollution increases, methods which disregard consumer impacts can understate total losses in surplus and grossly mis-state the distribution of these welfare effects.

TABLE 1. Studies of the economic effects of ozone on agriculture based on NCLAN data

Study	Region	Ambient concentration	Model features: Prices changes	Crop substitutions	Input substitutions	Quality changes	Crops	Results (1980 U.S. Dollars): Consumer benefits	Producer benefits	Total benefits
Howitt, Gossard and Adams (1984)	California	Universal reduction to 40 ppb†	Yes	Yes	Yes	No	18 crops	17×10^6	28×10^6	45×10^6
Adams and McCarl (1985)	Corn Belt	Reduction in NAAQS from 120 ppb to 80 ppb‡	Yes	Yes	Yes	No	Corn, soybeans and wheat	2079×10^6	-1411×10^6	668×10^6
Mjelde *et al.* (1984) Also Garcia *et al.* (1985)	Illinois	10% increase from 46.5 ppb†	No	Yes	Yes	No	Corn and soybeans	None	-226×10^6	-226×10^6
Adams and Crocker (1984)	U.S.	Universal reduction from 53 ppb to 40 ppb	Yes	Yes	Yes	No	Corn, soybeans, cotton	Not represented	Not represented	2200×10^6
Adams, Crocker and Katz (1984)	U.S.	Universal reduction from 48 ppb to 40 ppb	Yes	No	No	No	Corn, soybeans, cotton, wheat	Not represented	Not represented	2400×10^6
Adams, Hamilton and McCarl (1986)	U.S.	25% reduction from 1980 level for each state†	Yes	Yes	Yes	No	Corn, soybeans, cotton, wheat, sorghum, barley	1160×10^6	550×10^6	1700×10^6
Kopp, *et al.* (1985)	U.S.	Universal reduction from 53 ppb to 40 ppb†	No	Yes	Yes	No	Corn, soybeans, wheat, cotton, peanuts	Not represented	Not represented	1300×10^6
Shortle, Dunn and Phillips (1986)	U.S.	Universal reduction from 53 ppb to 40 ppb†	Yes	No	No	Yes	Soybeans	880×10^6	-90×10^6	790×10^6

†7 h growing season geometric mean. Given a log-normal distribution of air pollution events, a 7 h seasonal ozone level of 40 ppb is approximately equal to an hourly standard of 80 ppb, not to be exceeded more than once a year [Heck *et al.* (1982)].

‡Averaging time of 1 h; not to be exceeded more than once a year.

4. *As air pollution changes, percentage changes in total economic surplus are less than the percentage changes in biological yields which triggered these losses.* Any study which accounts for price effects of crop and input substitutions will obtain this result. The result is a direct outgrowth of micro-economic theory. Consider a deterioration in air quality. From the grower's perspective, the decrement in air quality is met by substitution of crops, cultivars, input combinations, and even growing locations. Consumers will respond analogously to any price increase; that is, they will substitute away from the good which has had an increase in relative price. Depending upon price elasticities, percentage gains in surplus could also exceed percentage changes in yields. Thus, the substitutions allow producers and consumers to attenuate the losses they would otherwise suffer from air quality declines.

5. *Air pollution changes can cause growers of pollution-tolerant crops to experience production changes greater than those initially suggested by the pollution increase.* This phenomenon is explicitly noted by Howitt, Gossard and Adams (1984), where growers of pollution tolerant crops like broccoli, cantaloupe, carrots, and sugar beets were also estimated to experience production declines along with growers of sensitive crops as air pollution increased. Studies of the corn–soybean–wheat economy in the U.S. Midwest have produced the same finding (e.g. Brown and Smith, 1984). This counter-intuitive result occurs because of a "crowding out" phenomenon. If, after a pollution increase, the pollution-sensitive crops continue to have higher returns per acre than the pollution-tolerant crops, and if inputs such as land and water are scarce, growers of the pollution-intolerant crops will substitute land, water, and similar inputs for air quality. The more profitable intolerant crops now require more land and water to produce the market equilibrium quantities.

6. *Changes in air pollution affect both the productivity and aggregate demand for factors of production.* Several studies based on NCLAN data have demonstrated that changes in air pollution will change the demand for specific inputs. Mjelde *et al.* (1984) estimate that a 10% increase in ozone in Illinois results in a 4% decline in the demand for variable inputs such as labor, water, and fertilizer. Howitt, Gossard and Adams (1984), Garcia *et al.* (1986), Kopp *et al.* (1985), and Brown and Smith (1984) have all shown that increased ozone increases the demand for land inputs.

These input demand effects result from two interdependent processes. First, if changes in air pollution are viewed as a neutral technological change, reductions in air pollution increase the productivity of all inputs proportionally. The productivity of any input in the agricultural production process is thus increased, increasing grower willingness-to-pay for the input. The second process that results in increased demand for *some* inputs refers to the "crowding out" phenomenon noted above. That is, some crops and regions receive a greater relative increase in yields from reductions in air pollution. Consequently, an expansion of individual crop acreage or total regional crop production may occur. This will result in an increase in aggregate input use in these more favored crops and regions. Conversely, crops and regions that do not realize net relative productivity gains from pollution control may reduce individual or total crop acreage, thus causing a reduction in aggregate input use. The exact nature of these input demand changes will be a function of the input mixes used for each crop or region and the relative effects of pollution changes within and across regions.

7. *The contribution of additional biological information to the accuracy and precision of economic assessments declines as the level of information increases.* How much plant response information is needed in order to perform credible economic assessments? Several NCLAN-related studies have attempted to provide guidance on this issue:

Adams, Crocker and Katz (1984); Howitt, Gossard and Adams (1984); Adams and McCarl (1985); Kopp *et al.* (1985); and Adams and Crocker (1984). Typically, these studies have focused on how the economic estimates change as the researcher changes assumptions about the nature of the underlying plant response data, such as functional form of the response model, number of observations on which to estimate such models and the number of cultivars over which to estimate "representative" response models. The results have generally demonstrated that the gains in economic precision (as measured by changes in the confidence intervals of the estimates) tend to decline as more information is obtained on each issue. These findings, however, do not mean that additional information on particular model parameters is never warranted. Rather, the costs of acquiring that information needs to be weighed against the consequences of being "wrong" with respect to the use of the model predictions.

8. *Changes in air pollution have differential effects on the comparative advantage of agricultural production regions.* Several NCLAN-based studies have focused on the consequences of air pollution across large geographical areas, such as the United States (e.g. Adams and Crocker, 1984; Kopp *et al.*, 1985; and Adams, Hamilton and McCarl, 1986). In order to represent correctly aggregate supply response across a large geographical region, economists typically define the large regions as being composed of a collection of distinct subregions representing different characteristics in terms of crop production alternatives, resource and environmental conditions, and other factors within each sub-region. A useful feature of such spatial equilibrium models is that the aggregate economic consequences of the policy alternatives as well as the effects of each policy on each subregion are measured. The NCLAN literature demonstrates that the economic effects can vary sharply across regions. For example, studies by Adams, Hamilton and McCarl (1986); and Kopp *et al.* (1985) indicate that reductions in air pollution result in gains to producers in areas simultaneously characterized by high ambient pollution levels and crop mixes dominated by air pollution sensitive crops. In such areas, the percentage gain in yields is greater than the overall reduction in agricultural prices at the national level, thus resulting in an increase in regional net income. This leads to expanded crop acreage. Conversely, areas with the opposite set of characteristics experienced reductions in revenues and acreages of some crops and hence a loss of "market share" for these crops. Thus, while these analyses all found net gains to society from reductions in air pollution, some subregions gained at the expense of others.

9. *Air pollution has economic transboundary effects that alter international trade flows with attendant gains and losses to exporters and importers.* The economic gains from free and open trade are well recognized. International trade in agricultural commodities has profound effects on the welfare of consumers and growers in both exporting and importing countries. A few of the recent NCLAN-based studies of U.S. agriculture incorporate a trade component into the model (e.g. Adams, Hamilton and McCarl, 1986; Shortle, Dunn and Phillips, 1986). Since much of the increase in agricultural output generally moves into the export market, the results of changes in air pollution have been to alter the supply of export commodities. The net effect is that foreign consumers of these commodities capture some of the consumer gains while foreign producers lose. Indeed, Adams, Hamilton and McCarl (1986) estimated that of the total consumer gains from ambient ozone reductions, 60% accrued to non-U.S. consumers. Conversely, increases in air pollution imply a reduction in the welfare of importing countries. As a result, national environmental policies can readily have transboundary *economic* implications even in the absence of a pollution transboundary phenomenon.

4. Challenges in assessing global climate change

The preceding discussions of extant economic assessments, including common themes and common limitations, have been drawn exclusively from the North American experience. These studies provide a consistent set of signals concerning the costs that air pollutants impose on agriculture in the U.S. and some regions of Canada. In addition, the list of observations common to these North American studies provides a set of restrictions that may be useful in formulating a common approach to similar research efforts in other pollutant, site, and time settings. Specifically, the economic inquiries into air pollution effects on agriculture are likely to have theoretical and empirical counterparts in water pollution and environmental and climate changes. Thus, information gleaned for the North American results can serve as a template for other studies.

However, some pollution effects on agriculture are a world wide phenomenon and may require a different policy perspective. Analysis and resolution of global pollutant issues, such as those inherent in the global climate change problem, creates a set of new challenges for researchers. The first such challenge pertains to the different orderings of economic processes, markets, and institutions across countries. This diversity requires an assessment framework that both exploits the common relationships between economic orderings while adequately representing the relevant individual characteristics of each country or region. The second challenge relates to a fundamental lack of biological data from which to predict crop responses across matrices of pollutant, site, and time combinations. Innovative procedures are required to determine the "transferability" of response parameters within this matrix.

A crucial starting point in economic analysis is the correct representation of the choice problem facing decision-makers. In market oriented economies the neoclassical paradigm of producer and consumer behavior provides an appropriate basis for such a representation. However, in many settings, individual supply and demand behaviors are essentially subsumed into planned, aggregate supply and demand decisions based on perceived social objectives. In addition to such planned, socialistic economies, a sizeable percentage of world food production and consumption occurs in developing countries, where the interaction of subsistence, village-oriented agriculture and aggregate food demand/production goals create a third possible configuration of market structures.

The challenge in measuring the international consequences of pollution on agriculture is to fold these diverse economic structures into a framework that provides some common measure of social welfare. Both the market oriented and planned economies have a somewhat common goal, namely, to produce efficiently a socially optimal level of agricultural output. Market oriented economies work toward this goal through the market signals created by the interaction of supply and demand forces. Planned economies rely on indirect approaches based on planning goals (i.e. perceived consumption needs) and associated allocations of resources to meet those goals. Interactive, iterative decision processes are frequently used to measure the contribution of alternative resource allocations to the attainment of the specified goals. However, a fundamentally different decision problem confronts the subsistence grower, who is both a producer and consumer of his output. Numerous behavioral models have been advanced to capture this dual role but in general it is believed that such growers are risk averse and thus produce first for family or local consumption using historically proven techniques. Production moves into domestic or international markets only after the primary goal of subsistence has been achieved. In this producer/consumer setting, pollution affects the individual in ways distinct from the cases heretofore treated. Specifically, while the

growers' quantity (yield) and quality of commodities may be reduced by pollution, as in any other economic setting, the effects on the grower may be more severe in terms of individual welfare. First, any productivity loss reduces marketable surplus and possibly even the subsistence component of production. Second, changes in quantity and quality of production may effect labor productivity if the grower's health is influenced, given that the grower (and immediate family) provide the major input, labor, into the agricultural production process. Third, pollution-induced yield reductions may intensify risk averse behavior, thereby reducing the likelihood of the grower adapting new, yield increasing technologies.

These unique dimensions of subsistence agricultural economies suggest that measuring the economic efforts of pollution on developing countries will require economists to incorporate some of these producer/consumer/labor supplier linkages into the assessment framework. Available literature on economic development may provide some guidance. In addition, the concept of the "household production function" proposed by Tinbergen (1956) and expanded by Lancaster (1968) offers a possible framework within which to explore the effects of pollution on the decision problem facing the producer/consumer.

5. Concluding comment

Wherever they have been done, prospective and retrospective assessments of pollution impacts upon agriculture provide convincing evidence of substantial economic effects having plausible policy relevance. Nevertheless the weight of the evidence cannot be interpreted as a call for a proliferation of biological and economic studies unique to each site, time, and food and fiber allocation system. Research funds and talents in any country are too valuable to permit this. As earlier noted, greater emphasis in the appropriate biological sciences upon axiomatic methods rather than mere replication has the potential to conserve research resources. The development of generic dose–response relations will greatly enhance model robustness, where robustness can be defined as the domain of circumstances where the model can be applied without undergoing structural revisions (Adams and Crocker, 1982). Development of generic models will take a long time, however. Alternatively, one might assume that a grand model exists which carries across nearly all sites, times, and allocation systems. One can then systematically exploit the exchangeability (transferability) concepts of Bayesian statistics set forth in Lindley and Smith (1982). These concepts test the existence of a common structure which generates random samples drawn from a number of distinct groups. They allow one to draw systematic and communicable inferences about the value of a parameter in one group from the observations on all groups. If exchangeability is complete, the identical model would apply to each group and one could then pool the data from all studies and transfer without revision the results for one group to any other group. At the other extreme, if exchangeability is utterly absent, then each group has its own unique structure and no transfer of results or pooling of data would be justified. Each group would be totally idiosyncratic.

Between these extremes, the Lindley and Smith (1972) formulation produces a weighted average of the data from other samples and data from the group (time, place, and allocation system) of concern, where the weights are determined by the precision of the pooled versus the individual sample estimates. Thus rather than having to conclude that dose–response functions and economic consequences across times, locations, and allocation systems either are totally similar or are totally dissimilar, one can evaluate the

exact extent to which they are similar. For many policy problems, the results from one setting, though not derived from a structure identical to that in the pollution setting of immediate concern, may nevertheless be close enough to allow full or at least adequate discrimination among relevant policy alternatives. Exchangeability allows the research planner to assess the degree of closeness among groups as well as implications of degrees of closeness for estimating payoffs of the policy alternatives.

Most of the evidence reviewed here about the levels of risk that prevailing ambient concentrations of photochemical oxidants cause producers and consumers of annual crops is derived from conceptually sound economic models and the best available plant science and aerometric data. There nevertheless remain important knowledge gaps, including inadequate information on response dynamics, environmental interactions, and the long-term and possibly irreversible effects of both gaseous and other pollutants on perennials. With the potentially outstanding exception of impacts upon perennials, it is unlikely, however, that inclusion of these possible improvements in future assessments would greatly alter the estimated overall aggregate benefits of reducing pollution levels. Bioeconomic sensitivity analyses suggest that changes in key natural science parameters must generally be substantial in order to translate into major changes in aggregate economic estimates. It is improbable that new natural science findings concerning functional forms, dose measures, or interaction effects for agriculture would exceed the magnitude of aggregate changes already addressed in some of the sensitivity analyses. There are likely to be countervailing responses that tend to offset errors, e.g., longer exposure periods may predict greater yield losses, but a combination of ozone and water stress tends to dampen yield losses attributed to ozone.

If more exact natural science information is to be of substantial value, it will probably be due to its contribution to better understanding of the manner in which the consequences of pollution impacts are distributed across groups and regions. The evidence reviewed makes it appear that production and consumption patterns, and thus distributional consequences, are often very sensitive to rather small changes in ambient pollution. At this time, it is not known whether estimates of the human behavioral responses which are the root sources of this sensitivity would be greatly altered by more exact natural science information.

The policy relevance of improved assurances about the sensitivities of production and consumption patterns to variations in pollution levels is perhaps most interestingly demonstrated by the consistent finding that agriculturists substitute other inputs, especially land, for poor environmental quality; that is, reduced environmental quality causes more land and inputs such as fertilizer and pesticides to be used. At this juncture, only the act of substitution has been thoroughly grasped. Its magnitude and the conditions that cause this magnitude to vary are presently little understood, although the finding that producer losses often increase exponentially implies that the worth of available substitution possibilities declines. To the economist, good natural science information is synonymous with a precise mapping of the substitution possibilities. The importance of such a mapping becomes apparent when one recognizes that land, fertilizer, and pesticide substitutions could be responsible for a good deal of the pollution that agricultural practices cause. Policy makers might then confront the paradox that the pollution from other sources which affects agriculture encourages agricultural practices which produce pollution. Conversely, a reduction in pollution from other sources could reduce some pollution that originates in agricultural practices. A thorough understanding of whether this quite plausible story is, in fact, true will require an as yet unavailable detailed natural science and economic understanding of influential substitution possibilities and behavioral responses.

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